Vol. V, No. 1, Spring 1957

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research trends

CORNELL AERONAUTICAL LABORATORY, INC., BUFFALO 21, NEW YORK

A New Air FOR ENGINEERS

by JOSEPH G. LOGAN, JR.

Electrons, Ions, and Atoms Complicate Flight Problems at Hypersonic Speeds

When the science of modern aerodynamics was first developed several decades ago, most of the aerodynamic theories were based on the assumption that air could be considered an incompressible fluid. Within the last decade, as the flight velocities of airplanes increased rapidly, it became necessary to consider compressibility effects, that is, the effects of change in density in the study of fluid flow. In the high subsonic and supersonic regimes up to flight Mach numbers of 5 the air could, however, be considered an ideal gas. This means that in the range of temperatures encountered up to a Mach number of 5 the molecular weight and specific heat of the air can be considered constant. These approximations have simplified many aerodynamic calculations.

In the past few years, the interest of aeronautical engineers has turned toward higher flight speeds and flight Mach numbers — to speeds up to 30,000 feet per second, about 30 times the speed of sound. In the regime between Mach numbers of 6 and 30, the "hypersonic" regime, the ideal gas concept of air must be abandoned. While this fact will be of principal import to the aeronautical engineer, its effects may extend even to the electronics engineer.

New Air Components

Air at room temperature is, of course, composed primarily of a mixture of oxygen and nitrogen molecules, about 21 per cent oxygen and 78 per cent nitrogen by volume. The remainder consists of small amounts of argon, water vapor, carbon dioxide, hydrogen, neon, krypton, and xenon. For the maximum temperatures encountered in the supersonic flight regime, engineers could regard the molecules of oxygen and nitrogen as rigid dumbbells. In this concept the molecular motions induced by collision were confined to translation and rotation. In the hypersonic regime the molecules of air have a much more complicated behavior (Fig. 1).

For example, the temperature behind a normal shock wave at a Mach number of 6 is about 1500°K (2240°F). As the temperature of the air gradually increased above this point, the molecules cease to behave as rigid dumbbells and begin to vibrate as a result of collisions. At a flow Mach number of 10 the temperature behind a normal shock wave reaches 3000°K (4940°F) and the oxygen molecules begin to break up or dissociate. At these temperatures the molecules and atoms also begin to ionize and collisions between

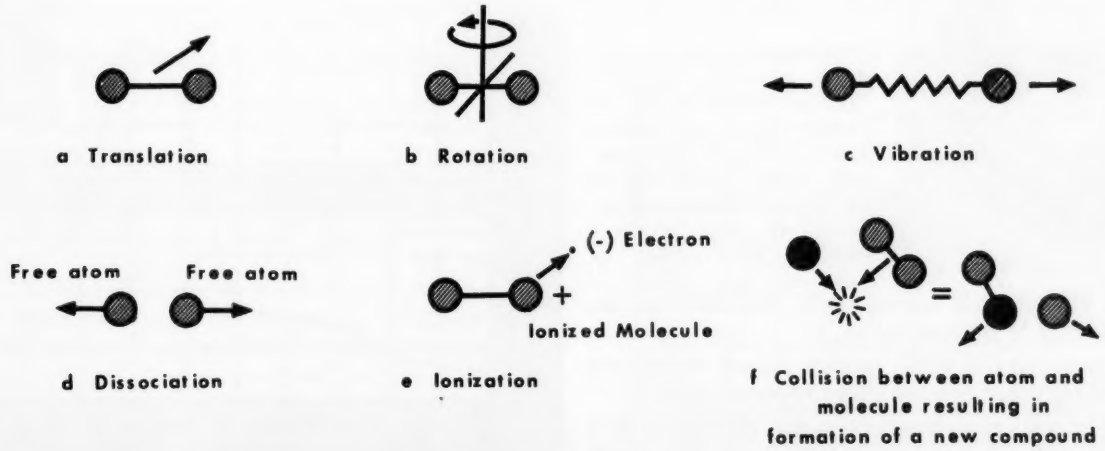
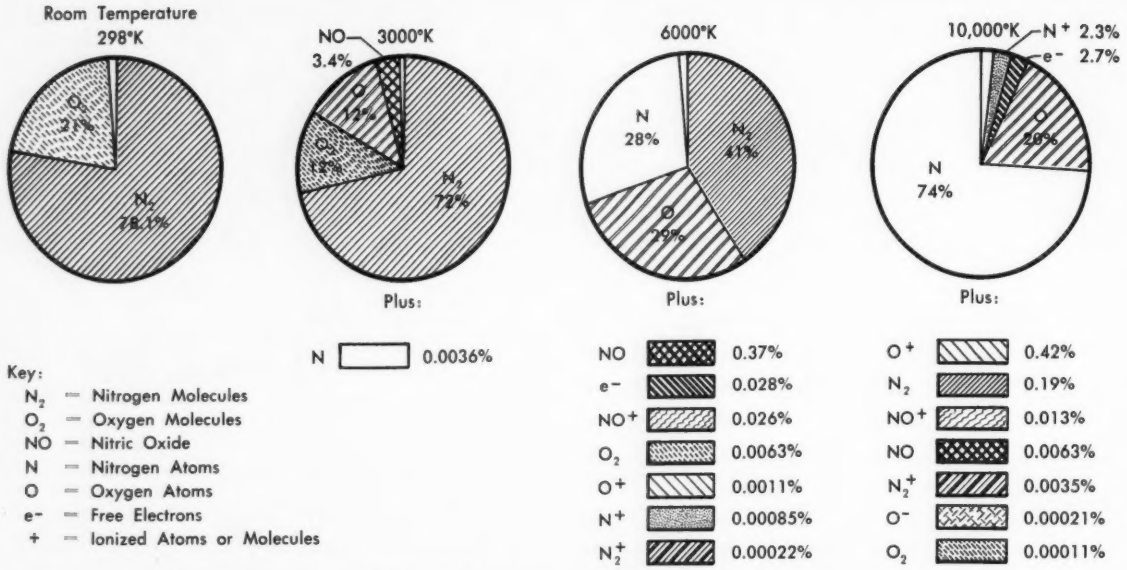


FIG. 1 — Degrees of freedom of a diatomic molecule.



(Note: The traces of argon, carbon dioxide, hydrogen, neon, krypton, and xenon remain present but unchanged at high temperatures. This chart needs therefore be concerned only with the changes in the oxygen and nitrogen content.)

FIG. 2 — Composition of high-temperature air.

molecules result in the formation of nitric oxide. Similarly, at a flow Mach number of 17 temperatures reach about 6000°K (10,340°F) and nitrogen begins to dissociate.

The extent to which the composition of air varies with temperature is clarified in Fig. 2. It becomes apparent that, as a result of the breakdown of oxygen and nitrogen molecules at temperatures of about 6000°K, the air can contain as many as 10 different components. The introduction of these new components alters the thermodynamic properties of the air, and forces the aeronautical engineer to discard many of the rules he has lived by for so long.

Flow Phenomena Modified

Several examples are cited below to show how aerodynamic flow phenomena are modified as a result of high temperature effects. Knowledge of these real gas (as opposed to ideal gas) effects is necessary for analysis of flow in hypersonic flight. The knowledge is vital, too, in the design of such hypersonic research facilities as the shock tunnel and in the interpretation of aerodynamic data obtained in these facilities. From these data will come the new aerodynamic information required to solve problems associated with flight at hypersonic speeds.

Recently, calculations of the "new" thermodynamic state of the air at high temperatures, including the specific heat and the speed of sound, have been carried out at CAL. A large increase in specific heat occurs as a result of the new ways in which energy can be distributed in air at high temperatures (Fig. 3). The chart reveals that the specific heat at constant pressure can

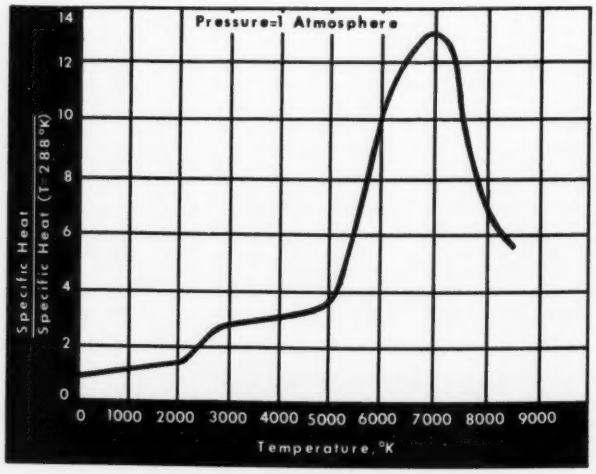


FIG. 3 — Variation of specific heat of air at constant pressure with temperature.

THE COVER

A technician lines up a 20-degree calibrating wedge in the test section of one of Cornell Aeronautical Laboratory's hypersonic shock tunnels. During initial runs in the tunnel schlieren photographs are taken to record shock waves formed by supersonic flow around the wedge. The flow Mach number can be determined from the angles formed by the shock waves.

Whenever the test section nozzle is changed the tests are repeated to calibrate the test section anew.

Similar tests have been made using miniature wedges placed at equal distances along the vertical axis of the tunnel. Variations in Mach number are noted and the necessary test changes made.

exceed the ideal gas value by factors of 12 at temperatures of 7000°K. In other words, it takes about 13 times as much energy to raise the temperature of a given mass of air one degree at 7000°K as at room temperatures. Engineers designing hypersonic shock facilities for operation in the 5500°K to 8000°K temperature range find this a real problem.

Another phenomenon observed is the decrease in the molecular weight of air as a result of the increase in the number of particles at high temperatures (Fig. 4). The equation of state must therefore be modified to include the molecular weight as a parameter. Normal shock calculations must also be modified to reflect the altered relations between pressure, temperature, and density. Accurate knowledge of the state of the air behind shock waves thus becomes indispensable to the the engineer making aerodynamic flight calculations.

Effects of Real Gas Behavior

The changes in those properties of air referred to as real gas effects may considerably alter the equilibrium phenomena in the flow field outside the boundary layer. The first marked effect of the real gas behavior on aerodynamic phenomena is observed in the temperature obtained behind normal shock waves as, for example, at the stagnation point on a blunt body. Since the amount of energy required to increase the temperature of air depends upon the number of ways in which the energy can be distributed among the air components, the introduction of any new degree of freedom requires that more energy be supplied in order to achieve a given temperature rise. Conversely, if there is a large number of ways in which the energy can be distributed, the gas temperature that can be obtained for a fixed amount of energy is always less in the real gas than in the ideal gas.

Consequently, as shown in Fig. 5, the actual stagnation temperature achieved behind normal shock waves

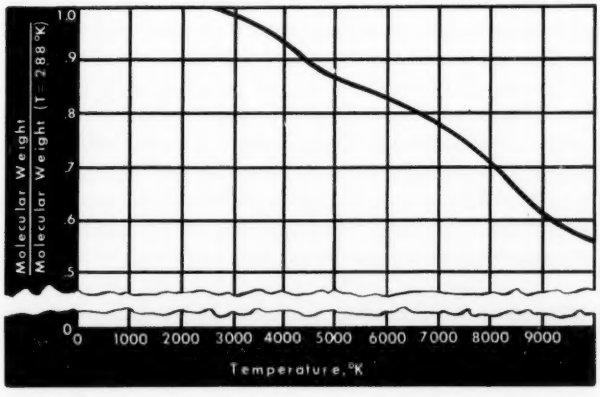


FIG. 4 — Variation of molecular weight of air with temperature.

is much lower than the temperature which would be calculated assuming that the air behaves as an ideal gas with a specific heat ratio of 1.4. The results shown are based upon the assumption that thermodynamic equilibrium is achieved behind the normal shock waves; that is, that sufficient collisions have occurred so that subsequent collisions do not alter the thermodynamic state.

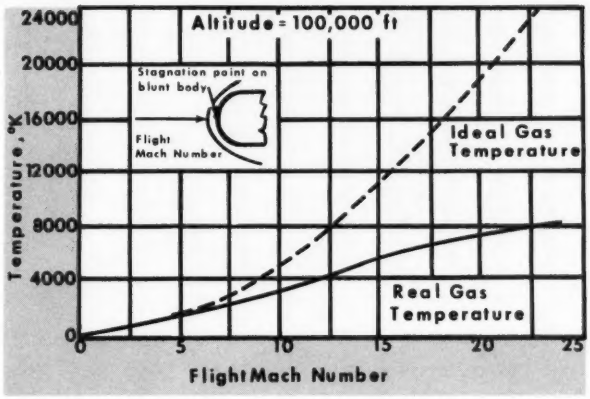


FIG. 5 — Stagnation temperature on a blunt body as a function of flight Mach number.

Another of the important differences observed between high temperature and low temperature flows at a given Mach number is in the shock angle on a wedge

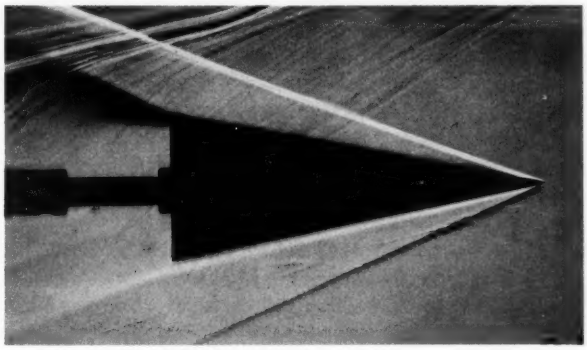


FIG. 6 — Flow over a two-dimensional wedge in a hypersonic shock tunnel. (Flow Mach number 5.)

(Fig. 6). This is important because measurements of attached shock angles are commonly employed in determining Mach numbers in wind tunnels. At a given Mach number large differences in shock angle can result from the thermodynamic changes occurring in high temperature air. The difference is most striking for the wedge angle for which the oblique shock just detaches from a wedge (Fig. 7). For real gas flows at high temperatures the oblique shock wave can remain attached

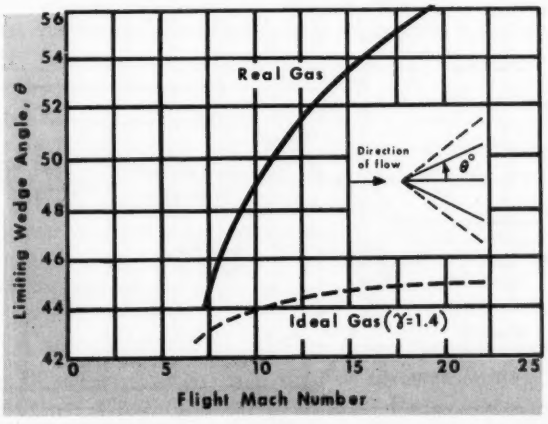


FIG. 7 — Limiting wedge angle in air as a function of flight Mach number.

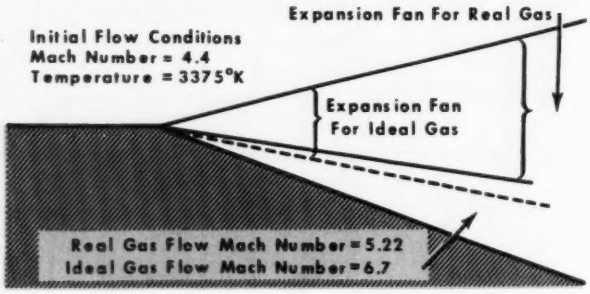

Expansion Fan For Real Gas
Initial Flow Conditions
Mach Number = 4.4
Temperature = 3375°K
Expansion Fan
For Ideal Gas
Real Gas Flow Mach Number = 5.22
Ideal Gas Flow Mach Number = 6.7

FIG. 8 — Comparison of the flow over a 20° corner for ideal and real gases.

for much greater wedge angles. This is one example of real gas phenomena employed experimentally to determine the state of the gas.

In two-dimensional steady flow expansions (known as Prandtl-Meyer flow) the actual flow Mach number increase across an expansion zone is smaller than would be calculated assuming ideal gas behavior. Fig. 8 shows that for supersonic flow expanding around a 20-degree corner the expansion zone is thinner and the final Mach number is smaller than those obtained assuming ideal gas conditions. Since the pressure distribution over aerodynamic bodies is related to the flow Mach number, it can therefore be expected that calculation based on ideal gas flow for pressure distributions over bodies will be inaccurate in high temperature flow fields.

As a final typical example, consider the effect of the real gas on the design of hypersonic test facilities. In the design of nozzles to obtain high flow Mach numbers, the nozzle expansion ratio required in a real gas is much greater than the one calculated assuming an ideal gas. Fig. 9 illustrates this effect.

Interpretation of Data

The interpretation of data obtained in such facilities also is largely dependent upon accurate calculation of tunnel flow conditions since, as yet, the problem of measurement of temperatures and pressures in short-duration, high-temperature, low-density flows has not been entirely solved. Before data obtained in these facilities can be reliably applied to full-scale bodies it is necessary, however, to learn much more about the air and its properties. One of the important problems being investigated at CAL deals with the actual state

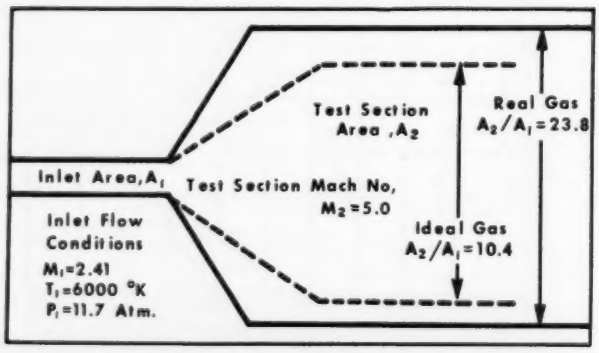


FIG. 9 — Expansion ratio for real and ideal gas in a hypersonic nozzle.

of the air in hypersonic shock tunnels. It has been assumed up to this point that the air in the high-temperature region has attained the aforementioned state of thermodynamic equilibrium. Each of the forms of excitation shown in Fig. 1 — translation, rotation, vibration ,etc. — requires a certain number of collisions between air particles in order to reach the equilibrium state. A finite time, known as the characteristic relaxation time, is therefore required for equilibrium to be achieved.

Hypersonic nozzles must be designed so that temperature changes do not occur so rapidly that the thermodynamic state lacks sufficient time to adjust to the altered temperature conditions. Knowledge of the relaxation times is therefore required and appropriate investigations for the different processes are being carried out at CAL and other laboratories. Initial studies have indicated that it may be necessary to consider the relaxation time in the design of nozzles so as to insure that thermodynamic equilibrium is maintained in regions of rapid expansion.

More Answers Needed

Interest in the problems introduced by the high temperature phenomena has triggered many new fields of research. As an example, this interest has led to studies of the kinetics of the formation of nitric oxide and has stimulated the development of a special shock tube for the investigations of chemical reactions at high temperatures.

Only a few of the many new problems introduced by the high temperature air phenomena have been discussed here. There are many others — for instance, the heating produced by radiation behind a shock wave may have important effects at high flight Mach numbers. Such problems are now being investigated in special shock tube facilities at CAL. There is also a sufficient number of free electrons present in air at temperatures above 3000°K (or above a Mach number of 10) so that the conductivity of the air is high. This high conductivity may pose serious communication problems. Further, it is to be expected that the real gas effects may modify the boundary layer and heat transfer phenomena. For example, above 3000°K the air contains many dissociated particles and if these particles diffuse across the streamlines and recombine at the wall the surface heating may be increased above that obtained without diffusion.

Consequently, aeronautical engineers are on the threshold of designing aircraft and missiles to fly through an entirely different medium — a medium whose ramifications are just beginning to be recognized and whose characteristics have been only sketchily explored. We call this medium a **new air** for engineers.

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"A Shock Tube Study of Dissociation Relaxation in Oxygen," Glick, H., Wurster, W.; Bull. Amer. Phy. Soc. Q-6, January, 1957 (New York City).

FORECASTING the WEAPONS *of Tomorrow*

by ROBERT H. SHATZ

Today we are living in an era of rapidly developing technology in which the only certain thing is change. At the same time we are attempting to maintain technological leadership in many fields, particularly in weapons, to offset the advances of our rival for world power.

The struggle for world power depends on how intelligently we apply our technology. Intelligent *selection* of new weapons must be made, because even this country cannot carry to completion all of the current weapon schemes of its scientists and engineers. Common sense quantitative prediction, therefore, is needed to help develop the best weapons systems for the nation's defense.

For the past eight years the Systems Research Department of Cornell Aeronautical Laboratory has been engaged in the relatively new field of weapons systems research — the explicit use of scientific method to aid military decision making. The Laboratory's objectives have been three-fold: to assist the Armed Forces in the selection and development of efficient weapons systems, to improve present systems, and to help create future ones. More recently, one other objective has been recognized: improvement and formalization of the methodology of weapons systems research.

Historical Background

In one sense this entire field was really started by the World War II operations research groups. Although the objectives of early groups were more limited than those of today's weapons systems research groups, since they were concerned with improving operations already in progress and the use of known weapons in known operational situations, their techniques and philosophy carry over into current work. Currently in the United States, the work in weapons systems analysis is being carried on by government, industrial and research organizations.

Although the weapons system analyst and the operations research analyst draw upon a common background and have many objectives that are quite similar, the latter deals more with future events, systems and weapons. The operations analyst tries to answer questions on operational decisions; the weapons system analyst tries to answer questions related to future development requirements and force structure.

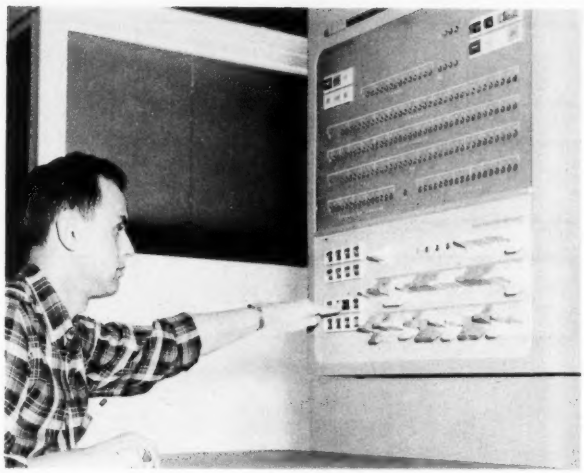


FIG. 1 — Problems of tactical air defense and of air traffic control systems, two of the major programs in the Systems Research Department, will now be computed on CAL's new IBM 704 digital computer. Although this automatic computing equipment will serve primarily in technical problem areas, it will also handle much of the Laboratory's administrative computation. Here, a CAL computer seated at the control console sets the equipment in operation.

Problems in Weapons Systems Analysis

When a customer from the Armed Forces or Department of Defense approaches a Weapons Systems Analysis Group, he may pose one or several problems. He may ask for studies of weapon systems requirements, for comparative evaluations of competing weapons systems, for studies of weapon employment, including tactical use and strategic effect, or for creation of good weapons systems specifications and the conceptual design of new systems. He may require work on any one of these problems, or on several of them as part of one major problem.

The Systems Research Department has had projects involving all of these problems, and although specific details are classified, some of the underlying logical and technical problems can be set down. In 1954, the Laboratory attacked the problem of providing a long-range air defense system for the United States. This was a typical case illustrating the systems requirements problem. The task was to develop the specific requirements in radar, aircraft and weapons, in order to provide improved defenses against manned-bomber aircraft and air-breathing cruise missiles in the airspace between the DEW radar line in the Arctic and the Pine Tree chain of radars along the Canadian border.

From this research, CAL could state the specific types of aircraft weapons systems that could be used for such operations and could estimate their relative effectiveness. Forces required to achieve various levels of defense were estimated. The research also included a study of how these requirements were affected by various changes in the enemy's attack tactics and the development of defensive forces.

A set of common-sense rules, based on experience and intuition, have proven to be of great value to the analyst in attacking these problems. First, as precise a problem statement as possible must be developed and evaluation criteria must be selected — that is, the prob-

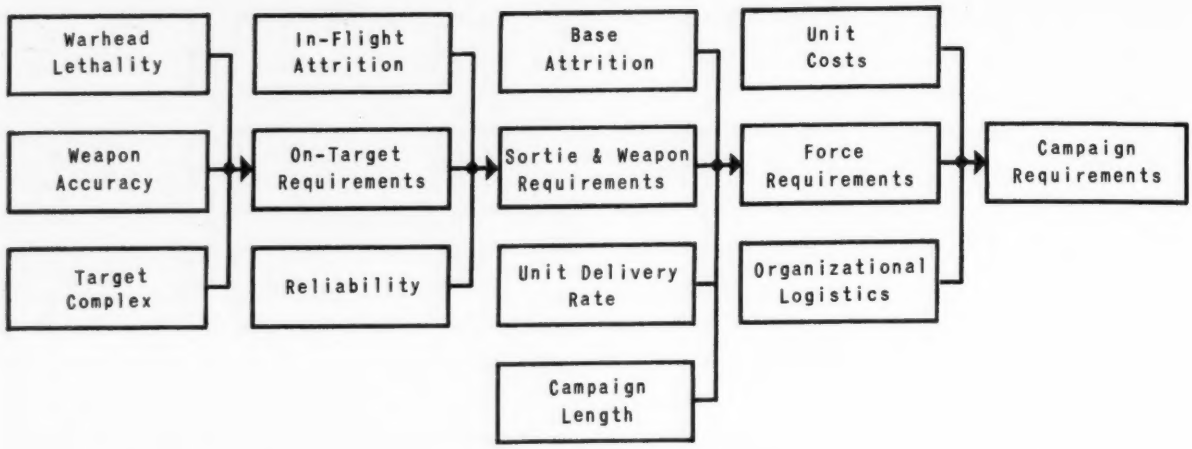


FIG. 2 — Campaign Model.

lem must be defined mathematically and a measure of effectiveness must be invented. Then, because the capabilities of the enemy and the exact status of his weapons timetable are not known, it is usually quite helpful to make a set of numerical assumptions on types of weapons, when they will be available, and how they will be used. Since these are assumptions, not facts, several values of these assumed inputs should be used and tested for sensitivity.

With respect to this problem of technical uncertainty, if all standard techniques of performance estimation do not give satisfactory results, the weapon systems analyst should assume that the gadget or system component works, and then ask the rather brutal question: "What good is it?" This concept, when used in systems context, will lead toward problem solution surprisingly often.

The general problem of how to interrelate the sometimes imposing array of interdependent subproblems is, of course, the basic challenge faced by the systems model which is a logical statement of the interrelations between the various factors. There are two fundamental ways to do this, and at the moment, not much choice between them.

Some groups always try for large symmetrical models which include everything on both sides. Other groups build smaller models of each major chunk of the problem, and then relate these to one another on a qualitative basis.

Of course, in all cases results will be relative rather than absolute. Therefore, answers based on small numerical differences should not be given too much credence, since a small difference in the final answer may be within the margin of uncertainty of the input data.

A Campaign Model

Let's take a close look at a comparative evaluation study which was performed by CAL, and at the campaign model which was used in the analysis (Figure 2). In this study the best atomic weapon delivery system had to be selected from seven competing systems. A campaign model, in which most of the factors of the problem were combined quantitatively, was designed with several objectives in mind. It was to evaluate comparatively a group of surface-to-surface atomic weapon delivery systems in a particular theater of operations. Also, it was to determine how operational effectiveness, costs and logistics vary with passive defensive measures adopted to reduce base and system vulnerability. The passive defensive measures considered were dispersal, base mobility and base hardening (physical protection) . The measure of effectiveness used in this study was the system costs of logistic requirements to achieve a given level of target destruction.

The problem was approached by an investigation of weapon characteristics, system characteristics and operational concepts. The study of weapon characteristics included performance, flight profile, accuracy, reliability and in-flight attrition. System characteristics which were studied included manpower, equipment, and cost requirements for a spectrum of tactical operations involving varying degrees of mobility, dispersal and base hardness. Operational concepts, established by Air Force officers, were investigated to determine preferred tactics and to optimize the degree of dispersal mobility and base hardness.

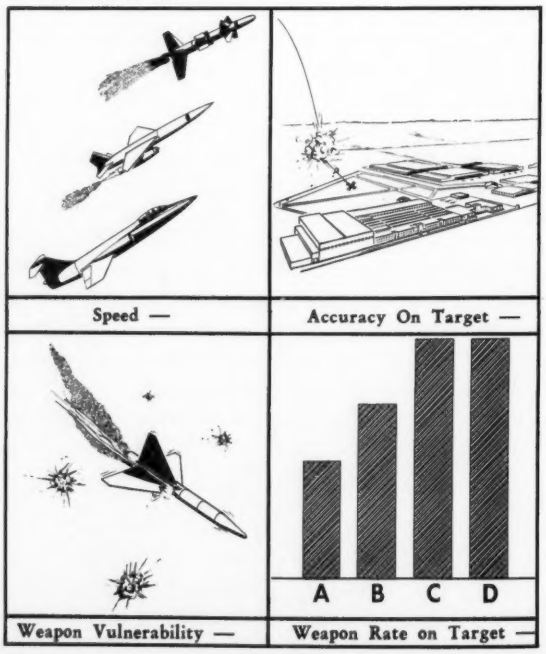


FIG. 3 — Systems research demands the evaluation of weapon capabilities.

Results of these analyses were then used as inputs in simulated campaigns. In each case the weapon under consideration was required to achieve a particular level of damage to a specified target complex. The system costs and logistics for this then became a measure of effectiveness of the weapon and provided a basis for comparison.

Knowing the warhead lethality for each weapon payload, for each weapon delivery accuracy and for each type of target, CAL's project team obtained on-target requirements. These were combined with the weapon in-flight attrition and reliability, and sortie and weapon requirements were computed. Force requirements were then obtained by including the data on base attrition, unit delivery rates and campaign length.

The In-Flight Attrition and Base Attrition blocks in the campaign model depended on assumptions regarding enemy capabilities and weapons characteristics. In this particular project the effect of changing these capabilities and characteristics on total campaign requirements was tested.

This problem required many computations. If it had been a dynamic problem, in which the various moves of combatants were played out in a symmetric war-game, even more extensive computations would have been required, solvable only with the help of computing machines.

Weapons Systems Analysis and the Designer

The ultimate objective of all weapons systems analysis is to provide the nation with the best weapons systems that can be developed. Unless the designer can translate weapons systems concepts into real and producible weapons, nothing at all has been accomplished. It is imperative, therefore, that systems designers and systems analysts exchange information and ideas.

Systems analysts can assist the designer in three important areas: in the selection of weapons systems characteristics, based on total mission capability; in critical comparisons with competing systems; and in program planning. The systems analyst will be cold-blooded in assessing the merits of the home team's inventions, and can help the design team's management to establish sound goals which will stand up for long periods of time. In many cases the systems analyst will uncover why a particular weapons system is not satisfactory; thus the research and development effort needed for improvement of the system can be planned more concretely. Unless the systems analysis team can do good work and is so placed in the organization that its results are obtained without much bias, however, none of these very useful things will occur.

Status of Weapons Systems Analysis Today

Weapons system analysis is a difficult field and as yet there are no really good methods for tackling dynamic problems which involve a great many uncertain factors. We know, too, that we are forced to work on problems of great importance to the nation, problems in which wrong answers are likely to be costly — in some cases dangerous.

Experience to date on results and how they stand up to the final test of time has been mixed. However, two things are quite clear. The attempts made by the analyst to provide quantitative answers to these difficult problems have been well worthwhile, and the answers have been better than those provided by any other approach. We should not quit because the problems are difficult, but rather we should increase the scale of our attack on how to improve methods and techniques.

Above all, the emphasis on fundamental research in methods of analysis must be increased. In this regard current work in this field must be improved, and can be, by the establishment of general solutions to such basic problems as the effect of countermeasures on weapons systems performance, the effect of morale in military organizations, and the quantitative assessment of complex command-control system performance.

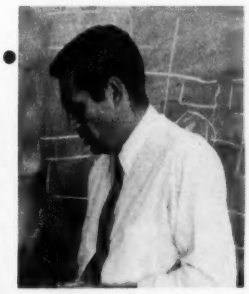
ABOUT THE AUTHORS

JOSEPH G. LOGAN, JR., author of numerous papers and reports on jet propulsion, heat transfer, supersonic flow and molecular structure, has done original research at CAL on both low and high speed valveless pulse jets. More recently, as head of the Theoretical Flow Physics Section, he has been engaged in investigations of gas-dynamics and hypersonic flow.

After receiving a B.S. degree in Physics and Mathematics from Miners Teachers College, Washington, D. C., Dr. Logan taught for two years in Baltimore and Washington. He joined the National Bureau of Standards in 1943 as a physicist, came to CAL in 1946 as an assistant research areodynamicist, and was named to his present position in 1956.

Dr. Logan has done graduate study at Cornell Universtiy and the University of Bufflo, where he received his Ph.D. degree in Physics in 1955.

He is a member of Sigma Xi, the American Physical Society and the Institute of Aeronautical Sciences.



ROBERT H. SHATZ, head of the Systems Research Department, leads all Laboratory effort on the development of weapons systems requirments and on military systems evaluation, including air defense, tactical air and missile systems. He joined CAL in 1948 as assistant department head of the Special Projects Group. He was named head of that Department in 1952, and appointed to his present position in 1955.

He received a B. Aero E. from New York University in 1940 and has done graduate study in mathematics there. From 1940 to 1943 he was employed by the Vega Aircraft Co., with responsibility for anti-submarine airplane development, and from 1943 to 1946 by the Lockheed Aircraft Co. as research engineer. He served as aeronautical engineer with the Office of Naval Research from 1946 to 1948.

He is a member of the IAS, the Operations Research Society, the American Ordnance Association and the American Rocket Society. He has represented the U.S. on several NATO air defense planning missions.

RECENT C. A. L. PUBLICATIONS

The Laboratory invites requests for its unclassified publications as a public service. Please direct your request to the Editor, Research Trends, Cornell Aeronautical Laboratory, Buffalo 21, New York.

"THE CALCULATION OF THE THERMODYNAMIC PROPERTIES OF AIR AT HIGH TEMPERATURES," Logan, Joseph G., Jr.; CAL Report AD-1052-A-1 (AFOSR TN-56-344); May 1956; 68 pages.

Procedures are described for the calculation, for air, of the equilibrium concentration and the thermodynamic quantities, energy, enthalpy, entropy, pressure, specific heat, molecular weight, and the speed of sound in the temperature range 1000°K to 20,000°K.

"TABLES OF THERMODYNAMIC PROPERTIES OF AIR FROM 3000°K TO 10,000°K," Treanor, Charles E. and Logan, Joseph G., Jr.; CAL Report AD-1052-A-2 (AFOSR TN-56-343); June 1956; 29 pages.

Tables are presented giving partition functions for the various components of high temperature air, temperature derivatives of partition functions, equilibrium constants for the high temperature air reactions, mole fraction concentrations of the constituents, and pressure, entropy, and enthalpy of the air.

"THERMODYNAMIC CHARTS FOR HIGH TEMPERATURE AIR CALCULATIONS (2,000°K to 9,000°K)," Logan, Joseph G., Jr.; CAL Report AD-1052-A-3 (AFOSR TN-56-342), July 1956; 25 pages.

A compilation of thermodynamic charts useful for shock waves and isentropic flow calculations in the temperature range 2000°K to 9000°K.

"EFFECTS OF WIND AND SPACE CHARGE ON CORONA POINT DISCHARGE, PARTICULARLY FROM AIRCRAFT," Chapman, Seville; CAL Report RA-766-P-11; Oct. 1954; 30 pages.

A discussion based on an instrumentation system which senses the electrostatic charge on aircraft and uses the information to control a high-voltage corona discharge point behind the tail of the aircraft, so that excess charge may be discharged by the corona point.

"FEASIBILITY STUDY OF A VORTEX TUBE ACOUSTIC TRUE AIRSPEED METER," Nicklas, James P.; CAL Report IH-942-P-1; Nov. 1955; 116 pages.

This report discusses a multiple-factor experiment which established the dependence of sound frequency on six variables; three variable-geometry vortex tubes were designed and fabricated for the experiment.

"TABLES OF TWO-DIMENSIONAL OSCILLATING AIRFOIL COEFFICIENTS FOR ROTARY WINGS," Loewy, Robert G.; CAL Report 77; Dec. 1955, 61 pages.

The complex values of lift deficiency function, section coefficient of lift at the quarter-chord due to plunging motions, and section coefficient of lift at the quarter-chord due to pitching motions about the quarter-chord are tabulated for many combinations of significant parameters.

"THE INFLUENCE OF GAS DISSOCIATION ON HEAT TRANSFER," Beal, John L. and Lyerly, Ray L.; CAL Report AD-993-M-5 (WADC TR-56-494); Sept. 1956; 43 pages.

This report discusses a program of experimental testing in which nitrogen tetroxide gas, N_2O_4, was used as the testing medium since it dissociates to NO_2 in a temperature-pressure regime which is adaptable to laboratory experimentation.

"PROPELLER BLADE STALL FLUTTER INVESTIGATION," CAL Report SB-950-S-2; May 1956; 58 pages.

This program was divided into experimental and analytical phases, and consisted of a systematic evaluation of important parameters in propeller blade stall flutter.

"PNEUMATIC BUILDINGS," Kamrass, Murray; reprinted from Scientific American; June 1956; 2 pages.

Supported only by thin air, these balloon-like fabric structures now house radar installations. Eventually they may also be used to roof over exhibition halls, hangars, and other large buildings.

"A MECHANICALLY IMPLEMENTED NORMAL ACCELERATION-LIMITING SYSTEM," Eakin, Grady J.; CAL Report TB-986-F-1; June 1956; 59 pages.

A normal acceleration-limiting system was investigated by means of an analog computer and a control simulator. The limiting system operates to drive the pilot's control stick forward at a constant rate, this action being taken on command of a signal consisting of several aircraft parameters.

"CREEP OF METALS SUBJECTED TO HIGH CURRENT DENSITIES," Hanlon, Francis E.; CAL Report KB-818-M-1; July 1956; 5 pages.

Tests were conducted on copper, type 347 stainless steel, and chromel wire at 1200°F and 1500°F. Temperatures were generated by passing alternating and direct current through the specimen.

"PERFORMANCE LIMITS OF A LOADED HYDRAULIC SERVO," Campbell, Graham F.; CAL Report FDM 257; Oct. 1956; 30 pages.

Calculations and results are presented showing the performance limits of a hydraulic position servo as influenced by the capacity of the servo control valve. The case is treated where the servo feedback gain is assumed high enough so that system performance can be considered linear until the servo-valve spool reaches its maximum deflection.

"DESIGN AND BENCH TEST OF A LOW-RANGE AIRSPEED INDICATOR FOR HELICOPTERS," Schelhorm, E. and Skelly, Eugene T.; CAL Report IH-885-F-3; Nov. 1956; 67 pages.

The bench testing of a refined low-range airspeed indicator shows it to be capable of measuring helicopter true airspeed around hover and also over the operating speed range of the helicopter.

"MAXIMUM RANGE OF A PROJECTILE IN A VACUUM," Shaffer, Dorothy B.; reprinted from American Journal of Physics; Nov. 1956; 2 pages.

The range-finding method described is based on the geometric properties of a Keplerian ellipse and provides a simple formula.